

Helioseismology as a New Constraint on SUSY Dark Matter

Ilídio P. Lopes, Joseph Silk and Steen H. Hansen

Nuclear & Astrophysics Lab., 1 Keble Road, Oxford OX1 3RH, United Kingdom

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ABSTRACT

The presence of dark matter in the solar neighbourhood can be tested in the framework of stellar evolution theory by using the new results of helioseismology. If weakly interacting massive particles accumulate in the center of the Sun, they can provide an additional mechanism for transferring energy from the solar core. The presence of these particles produces a change in the local luminosity of the Sun of the order of 0.1%, which is now within the reach of seismic solar experiments. We find that typical WIMPs with a mass of 60 GeV, annihilation cross-section of 10^{-32} cm³/sec, and scalar scattering interaction between 10^{-36} cm² and 10^{-41} cm², the lower end of this range being that suggested by the DAMA direct detection experiment, modify the radial profile of the square of the sound speed in the solar core by $\sim 0.1\%$. This level of change is strongly constrained by the most recent helioseismological results. Significantly more massive WIMPs have a much smaller effect on the solar core temperature profile. However future helioseismological experiments have the potential exploring most, if not all, of the WIMP parameter space accessible to current and planned direct detection experiments.

Key words: Sun: oscillations - Sun: interior - cosmology - dark matter

1 INTRODUCTION

The dynamical behaviour of various astronomical objects, from galaxies to galaxy clusters and to large-scale structure, in the observed universe can only be understood if the dominant component of the mean matter density is dark, amounting to $\Omega_m = 0.3 \pm 0.1$. Constraints from primordial nucleosynthesis of the light elements provide a compelling measure of the mean baryon abundance, $\Omega_b = 0.05 \pm 0.02$. The bulk of the dark matter is consequently non-baryonic, and the existence of particles that interact with ordinary matter on the scale of the weak force, so-called Weakly Interacting Massive Particles (WIMPs), provides one of the best-motivated candidates, arising from the lightest stable particle predicted by super-symmetry theories (SUSY), for resolving this problem.

One can show (Lee & Weinberg 1977) that if such a stable particle exists, its relic abundance is $\Omega_x h^2 \simeq 3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} / \langle \sigma_a v \rangle$, where $\langle \sigma_a v \rangle$ is the thermally averaged product of annihilation cross-section and relative velocity. Alternatively, if a new particle with weak-scale interactions exists, then its annihilation cross-section can be estimated to be $\langle \sigma_a v \rangle \sim 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ (Jungman *et.al.* 1996). Indeed, this constitutes one of the strongest arguments for considering the WIMP to be one of the best particle candidates for the non-baryonic component of the dark matter.

These particles are predicted by super-symmetry theories (SUSY) to be thermally produced at the early stages of the universe (Ellis 2001). The best WIMP candidates are neutralinos, but other types of WIMPs (axions, axinos, gravitinos and Wimpzillas) are not excluded as an alternative to the constituents of the dark matter component (Roszkowski 2001). Nor are charged super-heavy particles with strong interactions (Albuquerque *et.al.* 2000).

It is usually assumed that the WIMPs are a thermal relic of the big bang. The resulting thermic relic particle should have a mass inferior to 340 TeV , the unitary limit (Griest & Kamionkowski 1990). However, for SUSY models, this bound is typically 2 orders of magnitude stronger (Jungman *et.al.* 1996). The neutralino is the best candidate to be produced thermally, while CDM axinos, gravitinos and Wimpzillas are the best candidates to be produced by a non-thermal mechanism. For example, in the early Universe, vacuum fluctuations during or after inflation can produce a class of very weak super-massive particles with mass in the range of 10^{12} GeV up to 10^{13} GeV (Kuzmin & Tkachev 1999).

Many experiments around the world are currently engaged in searching for dark matter by assuming that it is dominated by the light neutralinos, as predicted by the minimal supersymmetric extension of the Standard Model (Ellis 2001). In particular, the DAMA collaboration (Bernabei *et al.* 2000) has reported evidence of an annual modulation of

recoil energy, which was interpreted as being due to scattering of some cold dark matter particles with masses between 50 and 100 GeV, and spin-independent cross-sections on a proton of between 10^{-42}cm^2 and 10^{-41}cm^2 .

Neutralinos might not constitute all the cold dark matter, but could be complemented by other particles such as axions and superheavy relics. Neutralinos are neutral Majorana particles, the lightest SUSY particles that are massive and stable (Jungman *et al.* 1996). Neutralino properties as dark matter candidates are quite dependent on the neutralino type, such as the bino, the wino and the two neutral higgsinos (Rowzkowski 2001). The neutralino cross-section for elastic scattering on a nucleus is expected to be typically very small, roughly 10^{-42}cm^2 . This is because the elastic cross-section is related to the cross-section of neutralino annihilation in the early Universe which must be only a fraction of the weak interaction strength in order to have $\Omega_x h^2 \sim 1$ (Bergström 2000). In this paper we adopt the neutralino as our WIMP test particle, unless stated otherwise.

The Sun traps WIMPs in the course of its lifetime, as we discuss below. If the Sun were to contain even a minute mass fraction of WIMPs, there could be a significant influence on its central thermal structure. Helioseismology provides a means for an independent test of the validity of this idea and can be used to discriminate between possible candidates for the Dark Matter (Kaplan *et al.* 1991). Indeed, helioseismology has become a mature discipline through the detection of more than three thousand solar acoustic modes with which it has been possible to constrain the internal structure of the Sun (Gough 1996). The large quantity of seismic data obtained by the ground-based network during the last 10 years, as well as the three seismic instruments on board the SOHO mission during the last 5 years, contributed to improve the accuracy of the frequency determination to a level of 1 part in 10^5 (Bertello *et al.* 2000; Garcia *et al.* 2001). This has allowed us to obtain a solar model for which the equilibrium thermodynamical structure accurately reproduces the observed seismic data, the so-called seismic solar model.

In this paper, we discuss how WIMPs can modify the evolution of the Sun and ultimately the present internal structure, namely in the nuclear region. In particular, we are interested in WIMPs that interact with baryonic matter through a weak interaction with a spin-independent scattering cross-section with values in the range of the current experiments for the detection of dark matter, such as the DAMA collaboration, and other ongoing or future experiments. It follows from our analysis that the possible WIMP candidates proposed by the DAMA experiment are in disagreement with our current models.

The next section contains a description of the present status of the standard solar model, and the current view of the different difficulties in modelling the observed Sun. In Section 3, we present a theoretical description of WIMPs and how they interact with baryonic matter. In particular, we discuss qualitatively the type of WIMPs capable of modifying the evolution of the Sun. In Section 4, we discuss solar models that evolve in halos of dark matter, and we discuss how those WIMPs can modify the evolution of the Sun. We conclude with a discussion of our new results, stressing their pertinence to the current status of the dark matter problem and Cosmology.

2 THE PRESENT SUN: THE SOLAR STANDARD MODEL

The Sun is a unique star for research because its proximity allows a superb quality of solar data, enabling precision measures of its luminosity, mass, radius and chemical composition. The Sun therefore naturally becomes a privileged target for testing stellar evolution theory. In recent years, different groups around the world have produced solar models in the framework of classical stellar evolution, taking into account the best known physics as well as all the available observational seismic data. This has led to determination of a well-established model for the Sun, the so-called standard solar model (Turck-Chièze & Lopes 1993; Christensen-Dalsgaard *et al.* 1996; Brun, Turck-Chièze & Zahn 1999; Provost, Berthomieu & Morel 2000; Turck-Chièze, Nghiem, Couvidat & Turcotte 2001, Turck-Chièze S. *et al.* 2001a; Bahcall, Pinsonneault, Basu 2001), for which the acoustic modes are in very good agreement with observation. Furthermore, this model has established considerable consensus among the different research groups, concerning the predictions of the solar neutrino fluxes, and has unambiguously helped define the difference between the theoretical predictions and the experimental results.

The combined effort between helioseismology and stellar astrophysics has contributed to strongly constrain the internal structure of the present Sun. Indeed, among the different seismic diagnostics that the solar model is tested against, the radial profile of the square of the sound speed is known with a precision as high as 0.3%, and in particular in the nuclear region this precision goes up to 0.2% (see Fig 1). This progress has been achieved through a detailed description of the microscopic physics, such as the nuclear reaction rates, the equation of state, the coefficient of opacities and the gravitational settling of chemical elements. More recently, the macroscopic mixing induced by differential rotation, seems to present a determining role in the evolution of the star. These physical processes take place in the thin shear layer, located between the radiative interior and the convection zone, the so-called tachocline (Elliott & Gough 1999).

The standard stellar evolution of the Sun assumes that the star is in hydrostatic equilibrium, is spherically symmetric and that the effects of rotation and magnetic fields are negligible. The present solar structure and evolution are computed starting from an initially homogeneous star of a given composition. The solar models used in this paper have been computed by using the CESAM code (Morel 1997). The main physical inputs are as follows. We used the solar composition of Grevesse, Noels & Sauval (1996), the OPAL96 tables of Iglesias & Rogers (1996), the equation of state of Rogers, Stenson & Iglesias (1996), the nuclear reaction rates of Adelberger *et al.* (1998), the Mitler (1977) prescription for the treatment of the nuclear screening rates, and the microscopic diffusion coefficients suggested by Michaud & Profitt (1993). The present structure of the Sun is obtained by evolving a initial star from the pre-main sequence, around 0.05 Gyr from the ZAMS, until its present age, 4.6 Gyr. The present solar model is obtained by choosing the initial Helium content, as well as the mixing length parameter of convection that best predicts the present solar luminosity and radius. The helioseismology requires that the present

structure of the Sun, including the global quantities, should be determined with a very high precision. In particular, the calibration of the solar radius is done with a precision of 10^{-5} .

3 THE EVOLUTION OF THE SUN IN THE PRESENCE OF DARK MATTER

In order to explain the rotation of spiral galaxies, it is necessary to assume that these are immersed in a halo of dark matter. In the present model, we assume the halo of the Milky Way to be an isothermal gas of WIMPs, the distribution of their velocities being Maxwellian with a mean velocity $\bar{v} \sim 240 \text{ Km s}^{-1}$. Furthermore, we assume that the local dark matter density near the Sun is about 0.3 GeV cm^{-3} (Jungman *et.al.* 1996). Typically, the local density by number is of the order of $3 \cdot 10^{-2} \text{ cm}^{-3}$ for WIMPs with $m_x \sim 10 \text{ GeV}$, and $3 \cdot 10^{-3} \text{ cm}^{-3}$ for WIMPs of $m_x \sim 100 \text{ GeV}$.

3.1 The WIMP scattering cross-section

Any WIMP that crosses the interior of the Sun may interact with a nucleus and lose enough energy to be trapped by the star's gravitational potential well. The WIMP interactions with the baryonic matter will depend upon their mass, m_x and on their scattering cross-section on the nucleons, σ_p . The elastic scattering cross-section of relic WIMPs scattering off a nucleus in the solar interior depends on the individual cross-sections of the WIMPs scattering off of quarks and gluons. For non-relativistic Majorana particles, such as the neutralino, these can be divided into two separate types. The coherent part described by an effective scalar coupling between the WIMP and the nucleus is proportional to the number of nucleons in the nucleus. The incoherent component of WIMP-nucleus cross section results from an axial current interaction of a WIMP with the constituent quarks, and couples the spin of the WIMP to the total spin of the nucleus. These two types of cross-sections have been computed exactly (Goodman & Witten 1985, Jungman *et.al.* 1996, and references therein), and in the case of scalar interaction it strongly depends on the particle physics model used. At this stage, it is worth noticing that in the case of scalar (or coherent) interactions, the total scattering cross-section is proportional to the mass of the nucleus, $\sigma^{sc} \sim \mu_i^2$, where $\mu_i = m_x m_i / (m_x + m_i)$ is the reduced mass, and in the case of axial (or incoherent) interactions, it can be shown that the cross-section, $\sigma^{ax} \sim \mu_p^2$, depends on the spin of the nucleus as $J(J+1)$. In the case of scalar interactions, because of the constructive interference between all nucleons in the nucleus, the cross-section rises rapidly with the atomic number and, as a consequence, WIMPs scatter much more efficiently on the heavier nuclei. Inside the Sun, elements heavier than hydrogen contribute substantially to the energy transfer and to the capture rate. Nevertheless, the Sun's evolution on the main sequence is strongly dominated by the production of helium rather than heavier chemical elements. In such a scenario, the helium nucleus will be the dominant source of scalar scattering, mainly due to its high abundance, given that heavier nuclei such as iron, nitrogen, carbon and oxygen are sub-dominant species. However, in more detailed studies on the capture of WIMPs by the Sun,

the contribution of heavier elements seems to be more significant than was previously thought (Gould 1987). In fact, the scattering on these species will increase the total number of WIMPs accreted by the Sun leading to a more significant change on the structure of the solar core. Consequently, by choosing to consider the scattering only for helium, we make a conservative approach to study the impact of WIMPs on stellar evolution and Helioseismology.

The essential particle physics parameters which enter the dark matter problem are the mass of the WIMP m_x and the elastic scattering cross-section, σ_p , of the various nuclei which constitute the solar material, and $\langle \sigma_a v \rangle$ the thermal average of the annihilation cross-section times the relative velocity of the WIMPs at freeze-out. The annihilation cross section can be calculated for each model (Krauss *et.al.* 1985) however, since we lack certain theoretical guidance, we decided to concentrate on a typical simple case for WIMP-nucleus scalar scattering, as previously discussed. We relate the cross-section of the WIMP on nuclei to the WIMP-proton cross section σ_p taken as a free parameter.

3.2 The Capture and Annihilation Rates of WIMPs in the Sun

The abundance of WIMPs in the Sun depends on the WIMPs accumulated in the Sun by capture from the Galactic halo and is depleted by annihilation. If N_x is the number of WIMPs in the Sun, then the differential equation governing the time evolution of N_x is (Gould *et.al.* 1987)

$$\frac{dN_x}{dt} = \Gamma_c - C_a N_x^2, \quad (1)$$

where Γ_c is the rate of accretion of WIMPs onto the Sun. The determination of Γ_c depends on the nature of the particle. If the halo density of WIMPs remains constant in time, Γ_c is time-independent. The second term accounts for depletion of WIMPs, and is twice the annihilation rate in the Sun, $\Gamma_a = 1/2 C_a N_x^2$. The quantity C_a depends on the WIMP total annihilation cross section times the relative velocity in the non-relativistic limit, $\langle \sigma_a v \rangle$, and the distribution of WIMPs in the Sun. The total annihilation cross-section of the new particle should possibly have a value that is consistent with the cosmological density of dark matter as specified, $\langle \sigma_a v \rangle \approx 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1} \Omega_x^{-1} h^{-2}$. It follows that, not knowing the initial content of relic WIMPs, Ω_x , we will consider different scenarios, such that $\langle \sigma_a v \rangle < 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ (Jungman *et.al.* 1996).

Solving the previous first-order differential equation, the total number of WIMPs at time t , is given by

$$N_x(t) = \Gamma_c \tau \tanh\left(\frac{t}{\tau}\right), \quad (2)$$

and the annihilation rate is given by

$$\Gamma_a(t) = \frac{1}{2} \Gamma_c \tanh^2\left(\frac{t}{\tau}\right), \quad (3)$$

where $\tau = 1/\sqrt{\Gamma_c C_a}$ is the time scale for capture and annihilation of WIMPs to equilibrate. As the age of the Sun is much larger than the equilibrium time-scale, $t_\odot/\tau \gg 1$, equilibrium is reached very rapidly, then $\Gamma_a = 1/2 \Gamma_c$. It

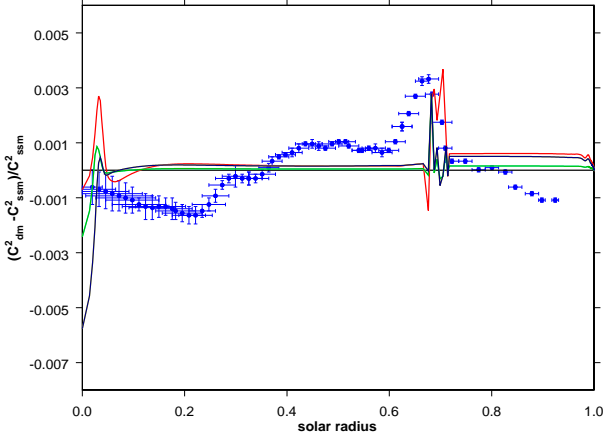


Figure 1. The relative differences between the square of the sound speed of the standard solar model and solar models, evolving within a halo of WIMPs. The continuous curves correspond to models with WIMPs with masses of 60 GeV, annihilation cross-section of $10^{-32} \text{ cm}^3/\text{s}$, and scalar scattering cross-section of 10^{-38} cm^2 (red curve), 10^{-36} cm^2 (green curve) and 10^{-40} cm^2 (dark blue curve). The peculiar form of these profiles occur as a consequence of the redistribution of energy by WIMPs inside the star. In the core ($r < 0.2 R_\odot$) the transport of energy by WIMPs decreases the temperature and the molecular weight leading occasionally to a reduction of the central sound speed. Reversely, in the outer layers, the energetic balance imposed by the calibration of the Sun, leads to an increase of the sound speed over all the solar envelope. The strong signature on the base of the convection zone ($r \approx 0.7 R_\odot$) is related with the effect on stellar evolution produced by the shear layer, the so-called tachocline. However, this effect should be carefully considered, once that it still remains an important source of incertitude. The curve with error bars represents the relative differences between the squared sound speed in the Sun (as inverted from solar seismic data) and in a standard solar model (Turck-Chi  ze, Nghiem, Couvidat & Turcotte 2001; Kosovichev *et al.* 1999; 1997). The horizontal bars show the spatial resolution and the vertical bars are error estimates.

follows that

$$\frac{t_\odot}{\tau} = 322 \left(\frac{\Gamma_c}{s^{-1}} \right)^{1/2} \left(\frac{\langle \sigma_a v \rangle}{\text{cm}^3 \text{s}^{-1}} \right)^{1/2} \left(\frac{m_x}{10 \text{ GeV}} \right)^{3/4}, \quad (4)$$

where t_\odot is the present age of the Sun (Jungman *et al.* 1996).

The rate of accretion of WIMPs in the Sun was first calculated by Press and Spergel (1985). Even though the detailed computation of the accretion can be quite elaborate, the basic idea is simple (Srednicki *et al.* 1987); if the WIMP elastically scatters from a nucleus with a velocity smaller than the escape velocity, $v_{esc} = \sqrt{2GM_\odot/R_\odot}$, then the WIMPs will be captured. The WIMPs have a typical velocity of the order of 300 km/s, which is smaller than the escape velocity at the surface of the Sun 618 km/s, consequently, they are trapped quite efficiently in the solar interior. If we consider that all the WIMPs that hit the Sun lose enough energy to be trapped, the trapping rate is given by the product of the surface area of the Sun, about $6.1 \cdot 10^{22} \text{ cm}^2$, and the flux of WIMPs, of about $n_x \bar{v}$. It reads $\Gamma_c = 4\pi R_\odot^2 n_x \bar{v}$. Gravitational focussing effects en-

hance the previous trapping rate by $2GM_\odot/\bar{v}^2$. This occurs because of the enlargement of the Sun's effective area due to the gravitational well and the requirement that the impact parameter be less than R_\odot . This yields a trapping rate of $\Gamma_c = \pi(2GM_\odot R_\odot) n_x / \bar{v}$. Bouquet and Salati (1989) have generalized and refined the capture rate for main-sequence stars (Salati & Silk 1989)

$$\Gamma_c = 10^{32} \text{ s}^{-1} \left(\frac{\rho_x}{1 \text{ M}_\odot \text{ pc}^{-3}} \right) \left(\frac{m_p}{m_x} \right) \left(\frac{300 \text{ kms}^{-1}}{\bar{v}_x} \right) \left[1 + 0.16 \left(\frac{\bar{v}_x}{300 \text{ kms}^{-1}} \right)^2 \left(\frac{M_\odot}{M} \right) \left(\frac{R}{R_\odot} \right) \right] \left(\frac{M}{M_\odot} \right) \left(\frac{R}{R_\odot} \right) \min \left[1, \frac{\sigma_p}{\sigma_\odot} \frac{M}{M_\odot} \left(\frac{R_\odot}{R} \right)^2 \right]. \quad (5)$$

The total number of WIMPs accreted, N_x , can be computed taking into account that $t_\odot/\tau \gg 1$, and is

$$N_x \simeq \Gamma_c \tau. \quad (6)$$

The total number of WIMPs at present strongly depends on the ratio $\sqrt{\langle \sigma_a v \rangle} / \Gamma_c$. If we consider $\langle \sigma_a v \rangle$ to be constant, the capture is weak and proportional to the scattering cross-section and N_x increases with Γ_c , for the case of low scattering cross-sections. On the contrary, for large scattering cross-sections, any WIMP which enters the star is captured, the captured flux saturates at the level of the incoming flux and the system reaches an equilibrium. Note that evaporation is unimportant for WIMPs in the mass range considered here, namely $m_x > 10 \text{ GeV}$ (Gould 1987).

This concentration of WIMPs in the solar core has a marginal effect on the evolution of the Sun. Luckily, the precision presently obtained by seismic diagnostics allows to determine in certain cases the effect of WIMPs on the solar core. In fact, a more accurate expression for the capture should take into account the way that WIMPs scatter from the nucleus through scalar interactions and/or axial-vector interactions, as well as second-order effects (Jungman *et al.* 1996). However, we choose to focus on a simplified picture in this first approach to the problem.

3.3 The energy transport by WIMPs in the solar interior

The energy transport by WIMPs in the solar interior is governed by three natural length scales: the mean free path of the WIMP, l_x , the inverse of the logarithmic temperature gradient, $\nabla \ln T$, and a typical geometric dimension of the system, such as the WIMP scale height, r_x . Bouquet and Salati (1989) showed that the WIMP distribution is approximately gaussian and therefore

$$n_x(r) = n_0 \exp \left[-\frac{r^2}{r_x^2} \right] \quad (7)$$

where $n_0 = N_x / \pi \sqrt{\pi} r_x^3$, and $r_x^2 = 3T_c / (2\pi m_x G \rho)$ which typically is $r_x \approx 10^{-2} R_\odot m_{100}^{-1/2}$ with m_{100} the WIMP mass in units 100 GeV.

There are two extreme regimes for the energy transport by WIMPs,

characterized by the values of the Knudsen number, K , defined as the ratio l_x/r_x . The Knudsen number strongly depends on the scattering cross-sections of the WIMPs on

nuclei, and typically goes like $K \approx 30 m_{100}^{3/2} / \sigma_{36}$ where σ_{36} is the scattering cross section measured in units 10^{-36} cm^2 .

In the case of small cross-sections, the WIMP mean free path is larger than the scale length r_x , $K > 1$, and two successive collisions are widely separated. This is the so-called large Knudsen number regime (or Knudsen regime). The transport of energy is non-local. Thus the WIMPs undergo few interactions on each orbit and therefore are not in thermal equilibrium with the nuclei. In such a case, it is convenient to define the average temperature of the WIMP core, T_x , as being the temperature of the star at r_x . At the center of the star, the WIMP temperature (or the averaged kinetic energy) is lower than the temperature of the nuclei, and in such conditions the net effect of the WIMP-nucleus collisions is to transfer energy from nuclear matter to WIMPs. Conversely, in the outskirts of the WIMP core, in certain cases the WIMPs give back the energy gained in the center of the star. This process is a very efficient mechanism at evacuating the energy from the nuclear region. In such a regime no precise analytic result exists. Nevertheless, an approximative solution has been found by Spergel and Press (1985). The luminosity carried by WIMPs can then be evaluated by

$$L_{lp}(r) = 32\sqrt{2\pi} \frac{\sigma_p \mu_p}{m_x + m_p} \int_0^r n_p(r) \bar{T}(r) n_x(r) r^2 dr \quad (8)$$

where \bar{T} reads

$$\bar{T}(r) = \sqrt{\frac{m_p T_x + m_x T(r)}{m_x m_p}} [T(r) - T_x]. \quad (9)$$

In the opposite limit, $K < 1$, the transport of energy is local and the energy transport proceeds by conduction, allowing for a much simpler treatment (Gilliland *et.al.* 1986). In this regime, the WIMP mean free path is much smaller than the dimension of the region where they are trapped. The WIMPs interact sufficiently often to be in local thermal equilibrium with the nuclei and therefore it is possible to define a temperature of the WIMP, which is equal to the temperature of the nuclei.

$$L_{sp}(r) = -4\pi r^2 n(r) \sqrt{\frac{T(r)}{m_x}} l_{sp}(r) \nabla T(r) \quad (10)$$

where $l_{sp}(r)$ is the local mean free path of the WIMP, it reads

$$l_{sp}(r) = \left[\frac{\rho(r)}{m_u} \sum \sigma_i \frac{X_i(r)}{A_i} \right]^{-1}. \quad (11)$$

The range of WIMP masses allowed by the cosmological model is quite large, even if we restrain ourselves to the WIMPs that are produced in a thermal scenario. Consequently, depending also on their scattering cross-section, the WIMPs can transport energy, not only in the conductive region and in the Knudsen regime, but also in an intermediate case. We have chosen to define the intermediate case as the one where the transport of energy is determined by the interpolation formula (Gilliland *et.al.* 1986)

$$L_x(r) = \frac{L_{lp}(r) L_{sp}(r)}{L_{lp}(r) + L_{sp}(r)}. \quad (12)$$

This formula appropriately converges to the right approximation in each of the two regimes, accordingly to the value

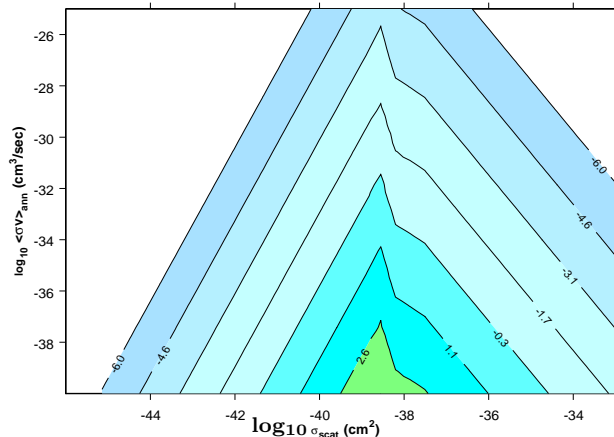


Figure 2. This figure presents the relative variation of the luminosity from the core of the Sun, due to the concentration of WIMPs in the solar core, as a function of scalar scattering cross section and annihilation cross section. The computation was made for a WIMP mass of 111 GeV. The iso-curves represent the decimal logarithm of the ratio of the luminosity of WIMPs against the Sun's luminosity in the inner core of 5% of the solar radius. The computation was made using the structure of the present Sun ($t_{\odot} \sim 4.6 \text{ Gyr}$) which was obtained by using an evolution code that assumes the evolution of the Sun under a standard evolution. In the solar models with scattering cross sections lower than 10^{-38} cm^2 , the increase of the luminosity of WIMPs with the scattering cross section is due to the increase on the number of particles trapped in the Sun's core. Alternatively, for the models with scattering cross sections above 10^{-38} cm^2 , the population of WIMPs inside the star is in equilibrium, and the increase of the scattering cross section leads to a less efficient energy transport by WIMPs, reducing the WIMP luminosity on the solar core.

of K . The errors introduced are within the precision of our computation.

4 DISCUSSION AND CONCLUSIONS

The thermodynamical structure in the interior of the Sun, namely in the nuclear region, is presently known with a precision of much less than a few per cent. This level of accuracy in constraining the solar interior has been achieved by a systematic study of the differences between the acoustic spectrum obtained from helioseismology experiments and the theoretical spectrum. Presently, this difference is less than $10 \mu\text{Hz}$ for almost all of the 3000 modes that probe the interior of the Sun (Gough 1996). This level of precision in the description of the solar core allows us to discriminate physical processes that could not be discussed otherwise, in particular those that present a peculiar behaviour, as seems to be the case for WIMPs trapped in the solar core. In Fig. 1, we compare the square of the sound speed, c_s^2 , of different solar models evolving within the presence of a halo of WIMPs and the solar standard model (Brun, Turck-Chièze & Morel 1998). The changes induced by the presence of WIMPs are concentrated in the inner core within 10% of the solar radius, typically seen in the profiles of the temperature, density and molecular weight.

Indeed, the WIMPs are thermalized within the solar

core and are on Keplerian orbits around the solar center, interacting through elastic scattering with the solar nuclei, such as helium, and thereby providing an alternative mechanism of energy transport other than radiation. The result is a nearly flat temperature distribution, leading to an isothermal core. Consequently, the central temperature is reduced. This reduction of temperature has two main consequences: since central pressure support must be maintained, due to the hydrostatic equilibrium, the central density is increased in the solar models with WIMPs, and since less hydrogen is burnt at the centre of the Sun, the central helium abundance and the central molecular weight are smaller than in standard solar models. The increase of the central density and hydrogen partially offset the effect of lowering the central temperature in the central production of energy. In fact, this is the reason why minor changes are required to the initial helium abundance and the mixing-length parameter in order to produce a solar model of the Sun with the observed luminosity and solar radius. This readily leads to a balance between the temperature, and the molecular weight in the core, leading to the peculiar profile of the square of the sound speed, $c_s^2 \propto T/\mu$. This seems to be the case for most of the solar models within WIMP halos. The balance between the temperature and molecular weight is critical for the profile in the center of the star, leading to some of the profiles presented in Fig. 1. In the same figure, we display the inversion of the sound speed obtained from the data of the three seismic experiments on board the SOHO satellite. It follows from our analysis that the presence of WIMPs in the solar core produces changes in the solar sound speed of the same order of magnitude as the difference between the sound speed of the standard solar model and the inverted sound speed. It is important to remark that the inversion of the sound speed still presents some uncertainty in the central region due to the lack of seismic data, mainly due to the small number of acoustic modes that reach the nuclear region. Furthermore, the inversions are not very reliable at the surface, above 98% of the solar radius, due to a poor description of the interaction of acoustic waves with the radiation field and the turbulent convection, namely, in the superadiabatic region (Lopes & Gough 2001). However, we can establish with certainty that the difference between the inverted sound speed and the theoretical sound speed is known with a precision of 0.3% in the solar interior, within 95% of the solar radius. The evolution of the Sun in a halo of WIMPs will increase the evacuation of energy from the solar core. The WIMPs will work as a 'cold bridge' between the core and the more external layers of the Sun. The magnitude of the effect is proportional to the total number of WIMPs concentrated in the solar core. Nevertheless, even if some systematic effect is present in the inversion of the sound speed, the presence of WIMPs in the solar core leads to a quite different nucleosynthesis history from the solar standard model case, and from that to a peculiar radial profile of the sound speed. In this way, the effect of WIMPs in the solar core can be inferred on the basis of seismic diagnostics, such as the inversion of the square of the sound speed, among other possible techniques. The proposed method constitutes a new way to disentangle the contribution of different non-baryonic particles to the dark matter.

The luminosity in the core of the Sun is presently known with a precision of one part in 10^{-3} . In the coming years, it

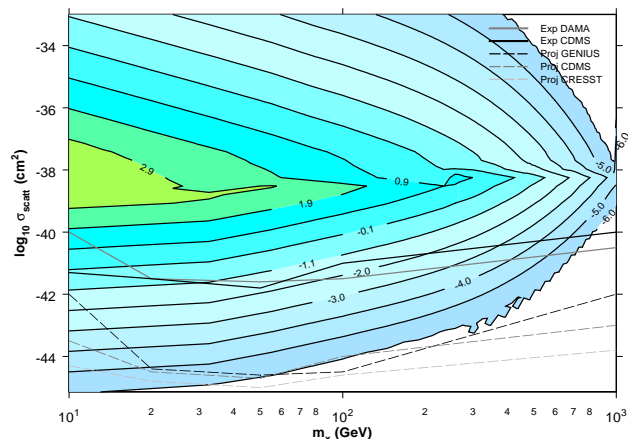


Figure 3. This figure illustrates the relative variation of the core luminosity of the Sun, produced in the solar interior by the presence of WIMPs, as a function of WIMP mass and scattering cross-section. Annihilation cross section is $\langle\sigma_a v\rangle = 10^{-36} \text{ cm}^2$. The representation is the same as the one presented in Fig. 2. The solid curves represent the current experimental bounds placed by DAMA (Bernabei *et al.* 2000; black grey solid line) and CDMS (Schnee 1999; black solid line), and the future projects of CDMS (black dashed line), GENIUS (Baudis 1998; black gray dashed line) and CRESST (Bravin *et al.* 1999; light grey dashed line). An important decrease in WIMP luminosity occurs for solar models with WIMPs with larger masses. This effect is produced by the reduction of the WIMP core, so that heavier WIMPs are more and more confined to the center of the star.

is very likely that the new seismic data available from the SOHO experiments, will allow us to obtain a seismic model of the Sun with an accuracy of 10^{-5} . In such conditions, the Sun can and should be used as an excellent probe for dark matter in our own galaxy. In Figs. 2 and 3, we compute the ratio of the WIMP luminosity against the Sun's luminosity produced in the inner core of 5% of the solar radius. A significant region of the $\sigma_{scat} - \langle\sigma_a v\rangle$ plot shows changes in the solar luminosity of the order of 10^{-3} . This order of magnitude on the luminosity produced in the solar core can be tested through seismological data. In particular, we are interested in the lighter WIMPs, $m_x < 100 \text{ GeV}$, and the smallest scattering cross-section, 10^{-45} cm^2 up to 10^{-40} cm^2 . This range of parameters are presently being tested by the DAMA and CDMS experiments, among others, and are also well within the range of the parameters of future helioseismological experiments (see Fig. 3). It is interesting to note, that the X-ray Quantum Calorimeter (XQC) experiment (D. McCammon *et al.* 2001) may exclude scattering cross sections bigger than about 10^{-29} cm^2 for the mass range considered here, relevant for strongly interacting massive particles recently hypothesised as an alternative dark matter candidate to WIMPs and that penetrate neither subterranean laboratories nor the solar core (Wandelt *et al.* 2000), hence being complementary to helioseismology in potentially excluding overlapping regions in parameter space.

If we believe in the simple model presented in this paper, DAMA candidate WIMPs with masses of 60 GeV and

annihilation cross-section of the order of $10^{-32} \text{ cm}^3/\text{s}$ cannot exist (see Fig. 1), otherwise their effect in the solar core should already have been identified by seismic diagnostics. However, we stress that in order to determine with certainty the range of masses and cross-sections for WIMPs that is in disagreement with the helioseismological results, a more careful analysis of the different regimes of energy transport by WIMPs should be done. Furthermore, the microscopic physics of this region of the star is not fully established, as there remains uncertainty in certain nuclear reaction rates, such as the $p+p$ reaction and the dynamical screening in other nuclear interactions such as $^3\text{He}+^4\text{He}$ and $^4\text{He}+^4\text{He}$.

An important diagnostic of the core can be obtained from the seismology of gravity modes. Indeed, it is the low-degree internal gravity modes that are the most sensitive to the conditions in the core, the region where substantial deviations from the so-called standard solar model might occur. Solar models evolving in the presence of dark matter have a g -mode period spacing that is drastically different from that of other solar models, mainly due to the peculiar distribution of density on the nuclear region that occurs as a consequence of the energy transport enhanced by the WIMPs. Therefore, g -mode observations could provide a sensitive test to the radial distribution of density in the solar core, and ultimately to the presence of dark matter in the solar neighborhood. The observation of gravity modes by SOHO seismic experiments, such as GOLF (Turck-Chièze *et al.* 2001b), could ultimately strongly constrain the physics of the solar core.

We have in this paper focused on a slightly simplified version of WIMP energy transport. There are several improvements which can be included in the analysis (Lopes *et al.* 2001), e.g. in the Knudsen regime the deviation from isotropy leads to a radius dependent luminosity suppression (Gould & Raffelt 1990b); in the conductive regime, the mass dependence of the thermal conductivity gives an additional factor $\sim 2\sqrt{m_{100}}$ for scattering on helium (Gould & Raffelt 1990a). Also inclusion of scattering off other light elements might affect the results slightly. Finally, the transition region between non-local and conductive energy transport could be expressed in terms of the Knudsen number (Dearborn *et al.* 1991; Kaplan *et al.* 1991) instead of the intuitive interpolation formula used here, which would be useful for a detailed investigation of the transition region.

In conclusion, we have identified the range of WIMP masses, scattering cross-sections and annihilation cross-sections which reduce the luminosity in the core of the Sun. These effects on the solar structure are now within the range of effects capable of being probed by the diagnostic capabilities of helioseismology. We did not concern ourselves with particular particle physics models, but considered a generic case, for WIMPs which have a large range of masses, scattering cross-sections and annihilation cross-sections. The effect of WIMPs in the core of the Sun is of the same order of magnitude as the microscopic physics and dynamical processes that are now being discussed in the framework of stellar evolution in the light of the most recent results of helioseismology. Studies of the sun and of cosmology may have much to gain from each other.

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